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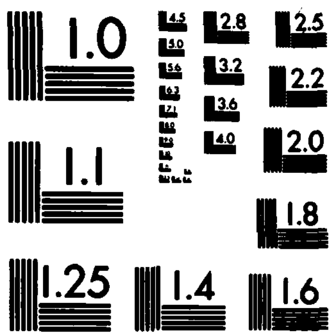

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two-phase supersonic flows dominate the structure of exhaust plumes of rocket engines with metallized propellants. Recent study has focused on the prediction of the characteristics of these exhaust plumes in order to evaluate plume visibility, radiation signatures and impingement effects. The objective of this study is to provide new experimental data on particle concentration, size distribution, transport effects, and particle interactions with shock waves in two phase jets. Progress in these measurements is decided in this annual scientific report.

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I. Research Objectives

This report summarizes studies being conducted to characterize the flow of a gas-particle mixture in an axisymmetric jet including the characterization of particle interactions with shock waves formed in the jet in compressible flow. The measurements include profiles of axial and radial velocity components of the particles, turbulence characteristics of the flow and particle velocity in the vicinity of the shock waves, both normal and oblique. Flow visualization is used to measure particle concentration and the structure of the shock waves. Samples extracted from the flow provide the particle size distribution in the jet. The experimental results of the study will be compared to existing computer codes for predicting two-phase jet flow. Solid particle-gas mixture flows have been examined in a wide variety of systems of engineering interest. Some of these are, for example, the pulverized coal combustion system in a power plant and small particles entrained in rocket exhaust plumes. There are, however, few measurements of particle-gas flow effects in heavily particle-laden two-phase jets and this is a major focus of the present studies.

Abramovich, et al. [1] investigated turbulent jets of different gases and measured the Prandtl and Schmidt numbers for those gases. They showed that both dimensionless numbers depend on the local density ratio between the two different gases. Rychkov [2] and Blagosklonov and Stasenk [3] showed that the gas temperature at the jet axis was increased and the particle temperature was decreased due to heat transfer between the two phases. The gas and particle temperatures equilibrated further downstream.

The Schmidt number is a measure of the diffusion of an additional phase through the gaseous phase. The effect of turbulence can be determined by comparing a turbulent Schmidt number with a laminar Schmidt number. Goldschmidt,

et al. [4] defined and interpreted the Schmidt number as a function of the velocity, concentration and particle size. Their Schmidt numbers in two-phase flow experiments were larger than unity and became larger with an increase in particle size. Abramovich and Girshovich [5] defined the Schmidt number as a ratio of the gaseous diffusion scale to the particle dispersion scale. Their Schmidt number was unity in the laminar air jet case, but it was less than unity in the turbulent air jet case. Hedman and Smoot [6] as well as Abramovich and Girshovich observed that the heavier particle in the two-phase system dispersed faster than the lighter particle.

In dilute-two phase jets with few solid particles, Hetsroni and Sokolov [7], and Popper, et al. [8] showed that the solid particle velocity is higher than the gas velocity in many regions of the jet. Other authors have investigated the characteristics of turbulence in a suspension of solid particles. Goldschmidt, et al. [4] and Hedman and Smoot [6] showed that turbulent transport is dependent on particle size distribution. Other studies have reported that the turbulent energy level decreases with the suspension of particles into a jet [7]. Carrier [9] showed theoretically that behind a shock wave the velocity of the gas is smaller than the velocity of the suspended particles and that the particles are then decelerated. Korkan et al. [10] observed no change in the particle direction through an oblique shock wave, even though the gas does change direction.

II. Status of Research

Previous studies supported by this grant have concentrated on the experimental characterization of gas-solid two-phase jet and nozzle flow. These studies have included the development of a flexible two phase flow facility, development and utilization of a new optical technique for measurement of particle concentration and the use of other diagnostic methods for measurement

of gas velocity and temperature, particle velocity and particle size distribution. The most recent measurements which have been made examined the effect of jet Mach number, particle size, particle loading and nozzle configuration on the detailed structure of the two phase free jet. In a theoretical study, expressions were developed relating gas-particle flow properties ahead of an oblique shock wave to gas-particle flow properties behind the shock wave. Recent publications detailing the results of these investigations are given in Section III. The major accomplishments of the past year of the research are outlined below.

A major difficulty which has been identified in earlier studies of ours was the observation that samples of 1 μm alumina particles would agglomerate in the particle feed system into particles about 10 to 15 μm mean diameter. This agglomeration was identified by our isokinetic sampling and scanning electron microscope analysis of collected samples and prevented the study of 1 μm particle suspensions. An aerodynamic method of deagglomerating the particles was developed. The technique involved adding a small converging-diverging nozzle to the tube feeding particles from the screw feeder into the flow channel leading to the experimental section. A simplified theoretical analysis suggested that with a shock wave at $M = 2.5$ at the exit of this small nozzle, the particles would experience the maximum drag after passing through the shock wave. This drag force is responsible for deagglomerating the particles and the design modification has been shown to reduce the agglomeration.

In previous studies we have developed an optical method to measure particle concentration profiles and presented measurements of solid particle concentration, gas velocity and gas temperature to evaluate the turbulent particle Schmidt number and turbulent gas Prandtl number in two-phase jet flows. It was found that the turbulent particle Schmidt number is large at the nozzle exit and

decreases slightly downstream. The turbulent gas Prandtl number is lower when particles are suspended in the flow than without particles. However, the thermal diffusion rate in air is similar to the viscous diffusion rate of air. In the present study, other aspects of heavily particle-laden two-phase jet flows are studied and described.

Experimental data and interpretation of those results have been completed for heat and mass transfer in an axisymmetric gas-solid two phase jet. The average values of turbulent gas Prandtl number and turbulent particle Schmidt number were derived from the measurements and used in interpretation of results. These dimensionless numbers were expressed as a function of Reynolds number. An important result is the finding that heavier particles disperse faster than lighter particles in the two-phase jet flows. A simplified treatment of the interaction between solid particles and turbulent eddies gave results which supported the conclusions of the experimental study.

When the turbulent gas Prandtl number is plotted against the gas Reynolds number as shown in Figure 1, the Prandtl number is seen to be independent of the gas Reynolds number. This result suggests that the rate of diffusion of gases is the same as that of thermal diffusion of gases in two-phase jet flows. The present results also imply that the turbulent particle Schmidt numbers become larger when the particle size is larger or the jet becomes faster. This means that the turbulent particle Schmidt number deviates from the single-phase case when the lag of particle properties becomes larger. Unlike the turbulent gas Prandtl number, the turbulent particle Schmidt number is dependent on the gas Reynolds number as seen in Figure 2. It is suggested in Figure 2 that the turbulent particle Schmidt numbers have a linear relation with the gas Reynolds numbers.

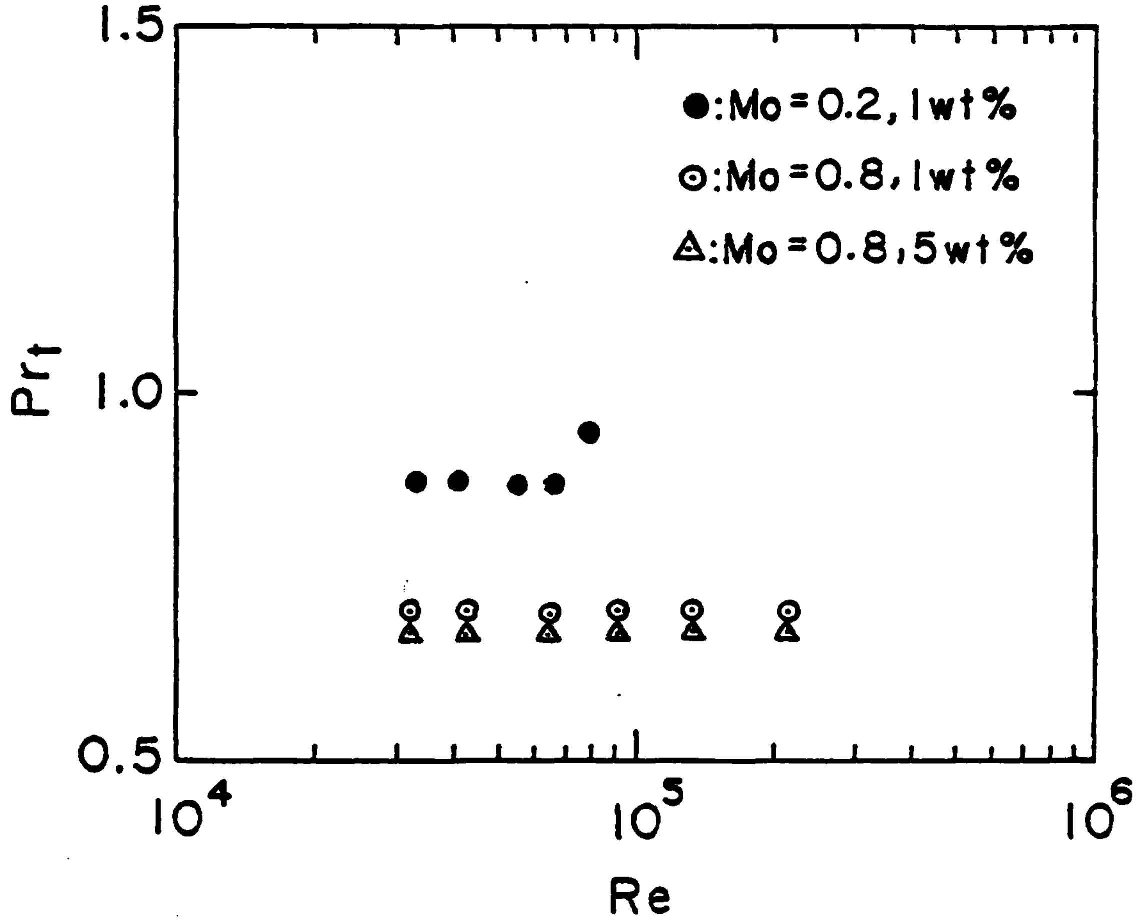

Figure 1

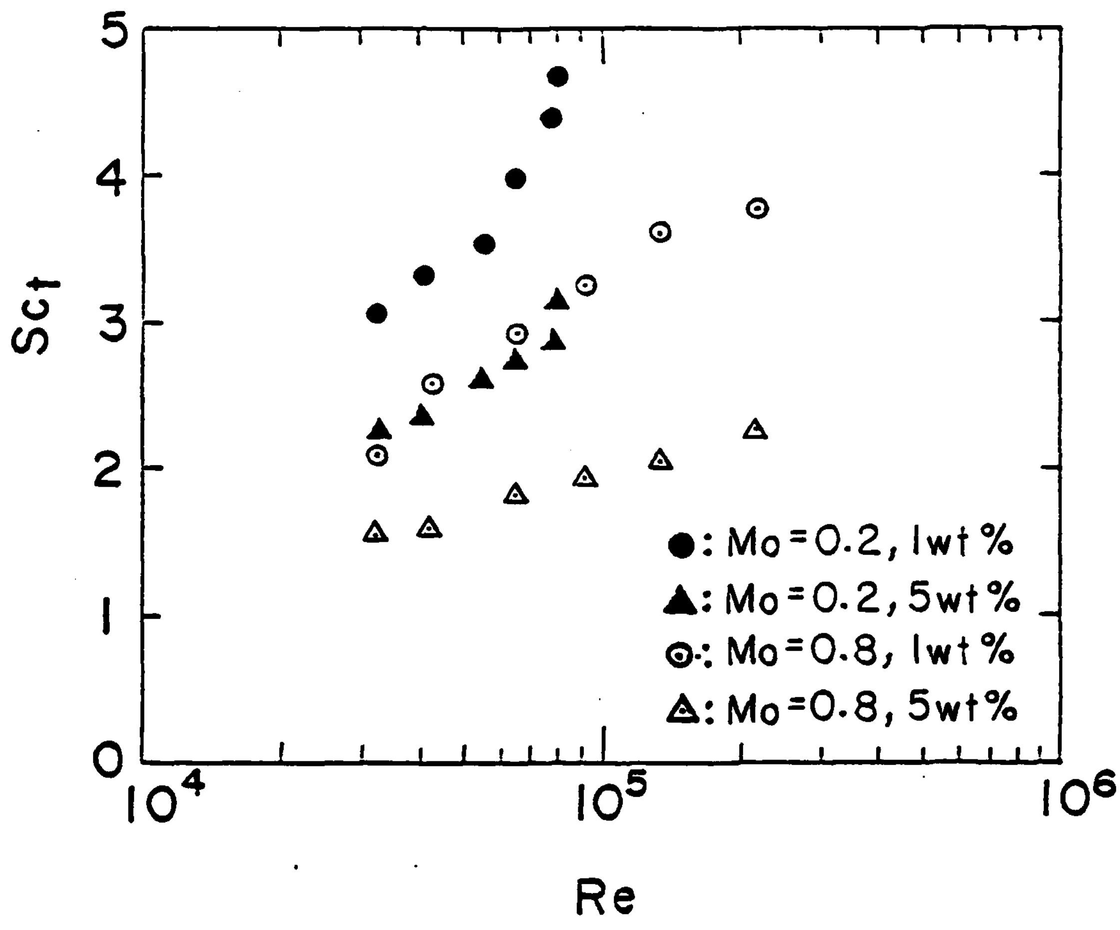

Figure 2

A dual beam, self-aligning LDV system is under development to measure the particle velocities. The system which is used in our experiments has a commercially available TSI counter-type signal processor. This signal processor serves as a high frequency filter which identifies and validates individual particle doppler bursts and calculates the frequency and hence corresponding particle velocity of the bursts. The data rate from the signal processor is very rapid and these data must be averaged externally to the signal processor. The electronics which is under development provides this data logging, averaging and statistical analysis.

The principal challenges presented by these investigations are the very high (~300 MHz) doppler signals characteristic of the optical arrangement used and the tradeoff between doppler frequency and spatial resolution. Heavily particle laden jets have additional problems of overlapping doppler bursts which must be separated from single particle bursts for accurate data interpretation. It is also clear from our earlier investigations that the particle velocities and trajectories are significantly different than the gas velocity for large (greater than 10 μm) particles (Figure 3).

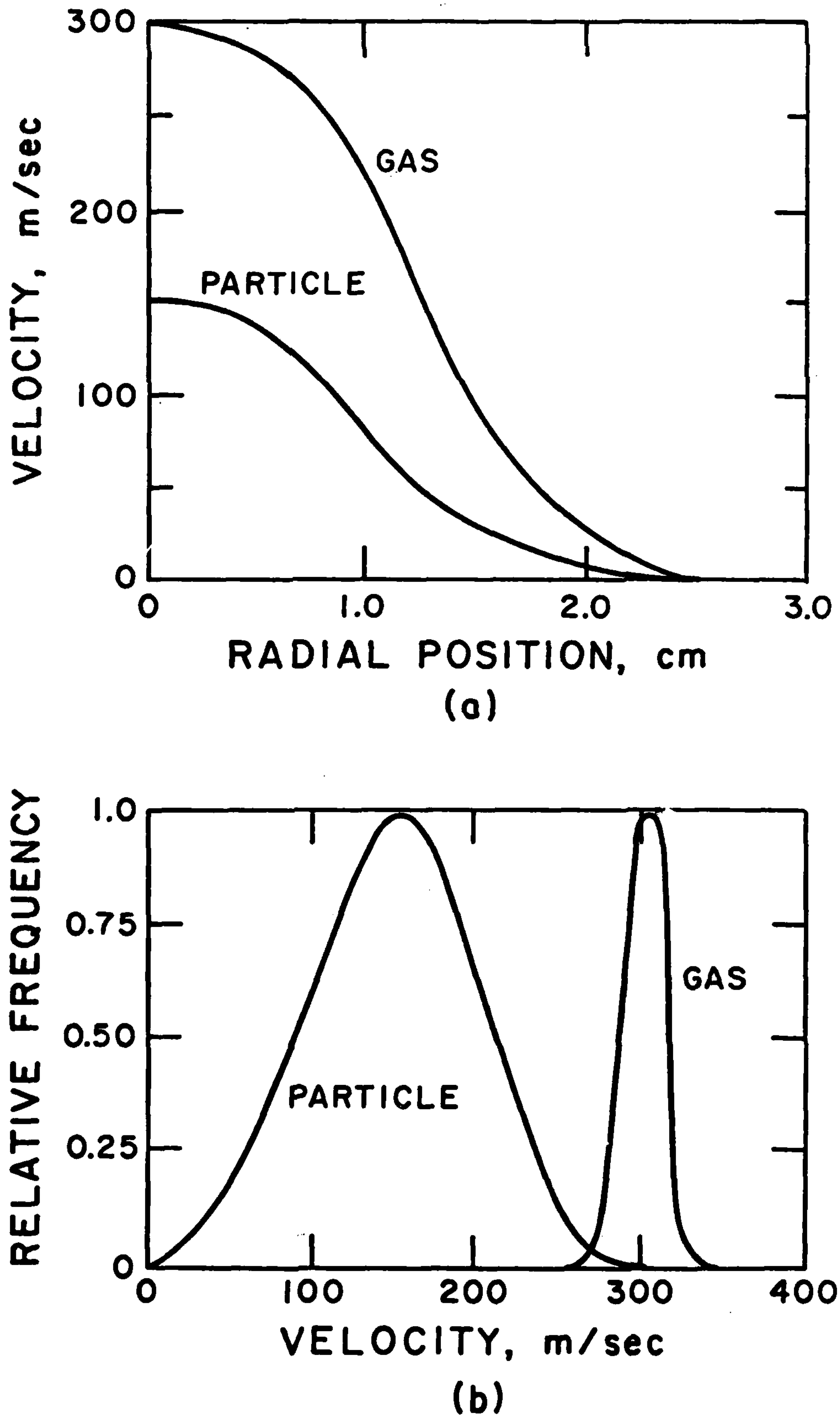

Figure 3. Gas and particle velocity in jet.
(a) Radial profiles, (b) Velocity distribution.
Expected results of measurements.

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IV. Publications

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2. K. Hayashi, "Measurement and Calculation of Properties of Gas-Solid Two-Phase Jets," Ph.D. Thesis, Mechanical Engineering Department, University of Colorado, Boulder, Colorado, December 4, 1980.

3. K. Hayashi and M. C. Branch, "Oblique Shock Waves in Two-Phase Flow," Eighth International Colloquium on Gasdynamics of Explosions and Reactive Systems, Minsk, USSR, August 23-26, 1981; also Progress in Aeronautics and Astronautics, in press.

4. K. Hayashi and M.C. Branch, "Particle Transport Effects in Gas-Solid Two-Phase Nozzle and Jet Flow," Paper No. 81-2100, AIAA 146h Fluid and Plasma Dynamics Conference, Palo Alto, CA, June 23-25, 1981.

5. K. Hayashi and M. C. Branch, "Gas and Particle Dispersion in Two-Phase Jets," Israel Conference on Mechanical Engineering, Tel Aviv, July 14-16, 1982, Israel Journal of Technology, under review.

6. K. Hayashi and M. C. Branch, "Some Aspects of Heat and Mass Transfer in Gas-Solid Two-Phase Jets," accepted for publication, Proceedings of the ASME/JSME Thermal Engineering Conference.

7. J. Seidle and M. C. Branch, "A New Procedure for Thermocouple Radiation Corrections," submitted to Journal of Heat Transfer.

8. K. Hayashi and M. C. Branch, "Flow of Gas-Particle Mixtures," Progress in Energy and Combustion Science, invited review, in preparation.

V. Personnel

1. Melvyn C. Branch, Associate Professor of Mechanical Engineering, Project Director and Principal Investigator.
2. Gary Shamshoian, Research Assistant.
3. Lionel Poincenot, Research Assistant.

VI. Interactions

Formal presentations of results obtained in this study have included a paper presented at the Israel Conference on Mechanical Engineering in July, 1982, entitled "Gas and Particle Dispersion in Gas-Solid Two-Phase Nozzle and Jet Flow." An oral progress report and abstract entitled "Flow of Gas Particle Mixtures" was presented at the AFOSR/AFRPL Rocket Propulsion Research Meeting, March 1982 in Lancaster, California. Another paper has been accepted for presentation at the ASME/JSME Thermal Engineering Conference in May, 1983.

Interaction with Edwards Air Force Base, California (Dr. Dave Weaver) and Aeronautical Research Associates of Princeton has been maintained to determine the availability of numerical prediction codes for two-phase nozzle and plume flow. Data obtained in the present study will be compared to predictions using these codes when they become available.

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